

TRANSIENT STABILITY PROMOTION BY FACTS CONTROLLER BASED ON ADAPTIVE INERTIA WEIGHT PARTICLE SWARM OPTIMIZATION METHOD

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Abstract. This paper examines the influence of Static Synchronous Series Compensator (SSSC) on the oscillation damping control in the network. The performance of Flexible AC Transmission System (FACTS) controller highly depends upon its parameters and appropriate location in the network. A new Adaptive Inertia Weight Particle Swarm Optimization (AIWPSO) method is employed to design the parameters of the SSSC-base controller. In the proposed controller, the proper signal of the power system such as rotor angle is used as the feedback. AIWPSO technique has high flexibility and balanced mechanism for the local and global research. The proposed controller is compared with a Genetic Algorithm (GA) based controller that confirms the operation of the controller. To show the integrity of the proposed controller method, the achievement of the simulations is done out in a single-machine infinite-bus and multi-machine grid under multi turmoil.

Keywords

Adaptive inertia weight particle swarm optimization, oscillation damping control, synchronous static series compensator, transient stability.

1. Introduction

Stability studies are mainly classified into two original areas: small signal [1] and [2] and transient [3] and [4]. Transient stability researches mention to the effects of abrupt and large turmoil [5] and [6]. Transient stability happens when the grid is able to tolerate the condition disturbance, such as a single or multi-phase fault or loss of generator [7].

FACTS devices can be connected in shunt, in series, or in a combination of both as shown in Fig. 1. With FACTS technology, such as shunt controller (Static Synchronous Compensator (STATCOM) [8] and [9], Static Var Compensator (SVC) [10]), series controller (Thyristor-Controlled Series Capacitors (TCSC) [11], Static Synchronous Series Compensator (SSSC) [12]), series-shunt controller (Unified Power Flow Controller (UPFC) [13], Thyristor Controlled Phase Shifter (TCPS) [14]), series-series controller (Interline Power Flow Controller (IPFC), impedance of lines, voltage of buses and phase angles in the grid can be regulated quickly and flexibly [15]. Therefore, FACTS controller can facilitate the power flow control, raise the power transfer ability, decrease the cost of the generation, and improve the stability and security of the network [16] and [17].

Many approaches have been made to assess the effect of FACTS devices to control network oscillations and transient stability improvement [18] and [19]. A nonlinear coordinated TCPS and generator excitation at the transmission line midpoint for promoting the transient stability of a network is proposed in [20]. A robust nonlinear coordinated generator excitation and TCPS controller is proposed in [21] for enhancing the transient stability of a grid, which a direct feedback linearization compensator via the excitation loop has been used for design to eliminate the interconnections and nonlinearities of the network. Three controllers such as Power System Stabilizer (PSS), TCSC and SVC are simultaneously used in [22] for increasing the stability and the damping network oscillations, with the proposed method being tested on a multi-machine grid. The SSSC is one of the main kind of FACTS family. It can be mounted in the transmission lines in series. By changing in reactance characteristic, SSSC is effective for controlling power flow in a power system [23] and [24].

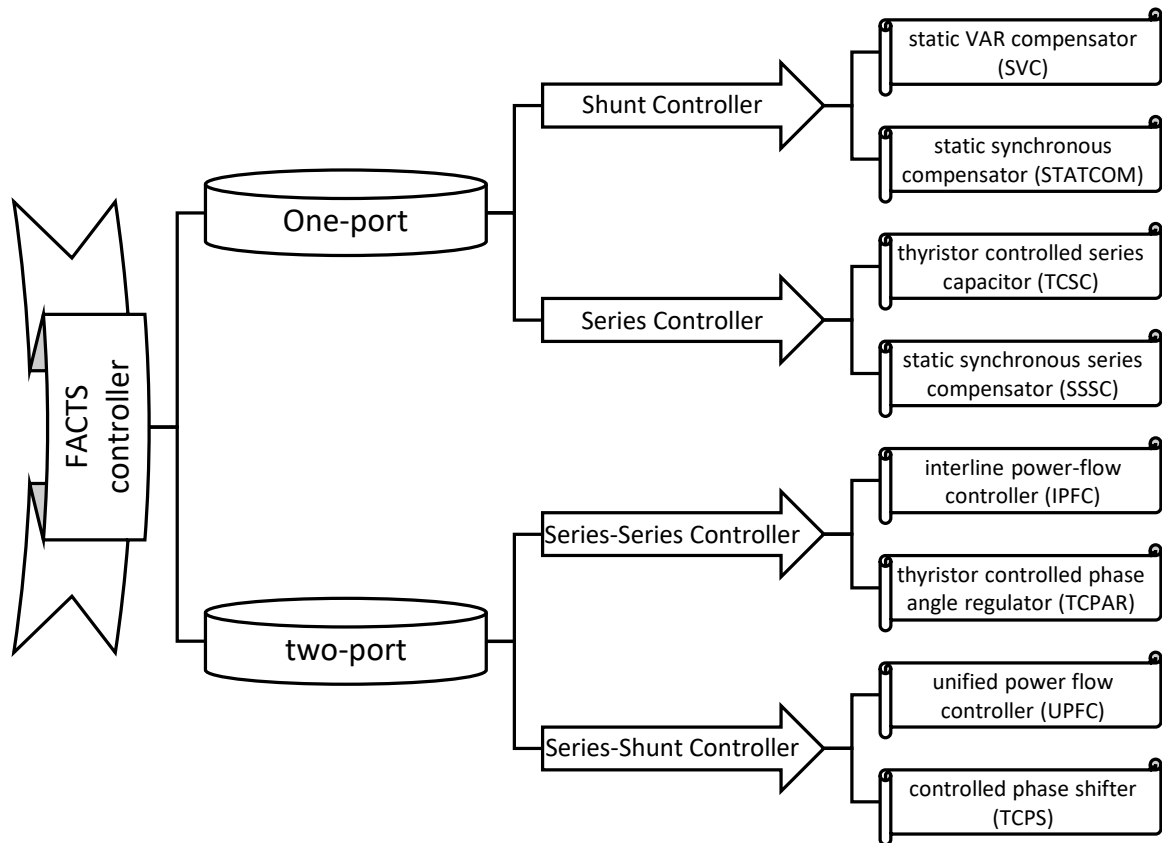


Fig. 1: Classification of the FACTS devices.

A developed multi-objective optimization method to design an SSSC-based controller to performance improvements of a network is proposed in [25]. The solution method based on Genetic Algorithm (GA) is applied for generating a Pareto collection of global optimal solutions to the granted multi-objective optimization problem. The effects of different control modes of the SSSC on two kinds stability in a simple power system based on modal analysis is presented in [26], which compares the effectiveness of active power and current magnitudes in a transmission line as a nomination for the input signal in the power oscillation damping controller. The nonlinear constrained optimization technique and location index proposed for the SSSC based on a circuit similarity of the electromechanical system is presented in [27] and a path independent structure keeping energy function technique is derived for the SSSC. In [28], in order to improve the network stability, a hybrid PSO and gravitational search method is used for designing a coordination structure composed of the SSSC and PSS. The impact of the constant quadrature voltage and constant reactance modes of the SSSC on the synchronizing torque, damping torque and transient stability limit of a radial grid is shown in [29].

The PSO technique and genetic algorithms have attracted significant attention between different mod-

ern heuristic optimization methods. Compare the two types of optimization methods contains the PSO and the GA for controller design to increase grid stability is presented in [30]. For optimal sizing and stay on of STATCOM and minimize the changes of buses voltage in a grid, an improved PSO is proposed in [31], where a multi-bus power system is used as a case to show the method. To set the parameters and determine the optimum location a stochastic technique using the PSO in a multi-machine grid, shown in [32], which by minimizing the objective function, increased small signal stability. A lead-lag controller for the SVC to reduce oscillations in the grid, which the use of GA optimization method for solving optimization problems and set PSS optimal parameters and supplementary controller, is proposed in [33].

In the application of PSO algorithm, there is a special regulation type called the AIWPSO algorithm [34]. This is based on the swarm population and a competitive and cooperative interaction can move toward the optimal solution. In contrast to the other heuristic methods, the AIWPSO algorithm has high flexibility and balanced mechanism for the local and global research. Rapid and easy calculations, simple implementation and fast convergence are some good aspects of this algorithm. Moreover, less storage memory is required in the optimization process [35].

In this paper, AIWPSO is proposed to adjust the utilized lead-lag SSSC controller for improving the grid transient stability. The performances of the proposed technique are evaluated under various operating states for both single-machine infinite-bus and multi-machine grid. Achievement show that the AIWPSO is able to find the best solution with statistical importance and better convergence. Also, the proposed algorithm has better performance in adjusting control parameters and better damping of network oscillation than the genetic algorithm [36].

2. Power System Model

The SSSC is connected in series with a network. It injects a voltage source in series with each line (Fig. 2). The nominal power of the generator is 1900 MVA including a turbine for rotating the generator and the governor. The exciting system consists of an automatic voltage regulator system. The generator is supposed to supply the power system at the nominal voltage level of 15.7 kV. Also, the consumer is fed by a 15.7 kV/500 kV transformer (T). As mentioned before, the SSSC is one of the main series compensators in the new grids. A Voltage Source Converter (VSC) is used to inject a variable and sinusoidal voltage (V_s) to the line [37]. In the SSSC, voltage amplitude and angle can be adjusted. There exist 90-degree difference between the injected voltage and current of the line.

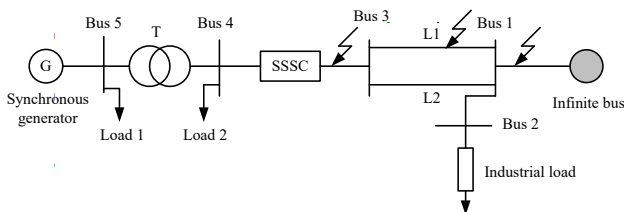


Fig. 2: Single-machine infinite-bus with SSSC.

In the SSSC circuit, a large portion of the injected voltage that is quadrature with the line current is utilized to improve the capacitive or inductive reactance of the transmission line. Therefore, the SSSC uses a virtual Voltage Source (VS) to control the line power flow by the management of the capacitive and inductive reactance of the line independently. The V_s set-point is adjusted through VSC in the secondary side of the connecting transformer. The compensation level can be controlled by dynamical change of the magnitude and direction of V_s both in the inductive and capacitive control modes [38] and [39]. In this study, Insulated Gate Bipolar Transistor (IGBT) and Pulse Width Modulation (PWM) technique are used for VSC operation. A constant voltage source which usually is a large capacitor will supply the required AC voltage. By the

conversion of this AC voltage to a specific voltage level, the line power flow is controlled.

3. Proposed Technique

3.1. SSSC Controller Structure

The input and output signals of the proposed SSSC controller are the rotor angle deviation ($\Delta\delta$) and the injected voltage V_s as shown in Fig. 3 respectively.

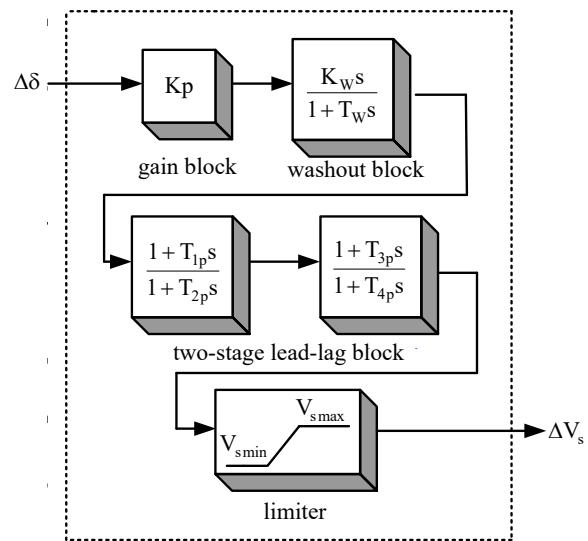


Fig. 3: Block diagram of SSSC-based controller.

Other parts of the controller are: gain block (K_p), washout block and phase compensation blocks. The phase compensation (time constants T_{1p} , T_{2p} and T_{3p} , T_{4p}) provides the suitable phase-lead characteristics to compensate the phase lag between the input signal and the output signal [40]. The value of washout time constant (T_w) is not critical. It may be in the range 1–20 sec. The accurate adjustment of the controller parameters is so effective to damp the transient oscillations of the grid in the fault situations.

3.2. Objective Function Optimization

The optimal design of the SSSC controller will improve the stability of the grid. In order to have a criterion for comparison, a suitable objective function should be introduced and used during the optimization process. When a disturbance happens in the grid, the total network will experience the variation. This variation can be in any of the parameters of the power system. The variations of the speed, rotor angle and power flow can be lonely or altogether be considered as the goal function to be minimized. The minimization of Integral

Amplitude Error (IAE) which is, in fact, the rotor angle deviation and rotor speed deviation is the main objective of this study.

$$M = \sum \int_0^{t_1} t |\Delta\delta(t, X)| dt, \quad (1)$$

$$H = \sum \int_0^{t_1} t |\Delta\omega(t, X)| dt, \quad (2)$$

where M and H are the objective function of the single-machine system and multi-machine system, respectively. X is the optimization parameters of the controller ($K_P, T_{1P}, T_{2P}, T_{3P}, T_{4P}$), and t_1 is the time of simulation. To evaluate the objective function, simulation of the power system must be done during the simulation time. Then, by using settling time, the overshoot value and also giving weight to each of these variables, the objective function is calculated. The goal can be formulated as the minimization of multi-objective function H given by:

$$\text{Minimum } M \& H, H = (H_1, H_2, \dots). \quad (3)$$

The limit constraints on SSSC controller variables are given by:

$$K_p^{\min} \leq K_p \leq K_p^{\max}, \quad (4)$$

$$T_{ip}^{\min} \leq T_{ip} \leq T_{ip}^{\max} \quad i = 1, 2, 3, 4. \quad (5)$$

The traditional methods for adjusting the SSSC controller parameters cannot give the optimal value and their performances mainly depend on trial and error indication. In the new modern methods based on the evolutionary algorithms, the optimization process is based on the simulation time and the objective function value. In this paper, the AIWPSO approach is used in comparison with the other evolutionary algorithm such as the genetic algorithm. It is shown that AIWPSO is much more accurate and fast.

4. AIWPSO Algorithm

The AIWPSO is a modified version of the classical PSO [41] and a stochastic optimization algorithm. Therefore, its high ability in solving complex numerical problems has gained much popularity. This algorithm instead of inspiring by the evolutionary mechanisms is inspired by the social behaviors of some animals such as fish and birds. The behavior of each swarm is based on some social rules such as velocity coordination with the near particles and acceleration rate depending on the distance, generally the main characteristics of the intelligent. Particles are compatibility, diversity of response, nearness, good quality and stability. This algorithm has a population consisting of vector

$\vec{X} = (X_{i1}, X_{i2}, X_{i3})$ with N particles. Each element of the vector \vec{X} is a parameter of the SSSC controller. In the beginning, the population is initialized randomly. During the optimization, the particles are moved toward the optimal solution of the investigated problem. The position of each particle is shown by vector \vec{X} and its value is determined by the objective function. During the optimization process, the best experience of each particle and its position are stored. The best experience for the i -th particle is $P_{best,i}$ and its position is $X_{best,i}$. Accordingly, the best global value and position among the population are shown by $X_{gbest,i}$ and $X_{best,i}$ respectively. The velocity and position of each particle in each movement are updated as follows:

$$\begin{aligned} \vec{V}_i(t+1) &= \\ &= \omega \cdot \vec{V}_i(t) + r_1 C_1 \text{rand}_1(\vec{X}_{pbest,i} - \vec{X}_i(t)) + \\ &\quad + r_2 C_2 \text{rand}_2(\vec{X}_{gbest,i} - \vec{X}_i(t)), \end{aligned} \quad (6)$$

$$\vec{X}_i(t+1) = \vec{X}_i(t) + \vec{V}_i(t+1), \quad (7)$$

where ω is the inertia weighting factor, C_1 and C_2 are the acceleration factors. In order to make the nature of the movement randomly, C_1 and C_2 are multiplied by the random variables r_1 and r_2 . Usually, a low ω leads to a fast convergence to a locally optimal solution when high values may deprive the algorithm of convergence. In the AIWPSO, during the optimization process, ω changes linearly from one to zero as shown below:

$$\omega = \omega_{\min} + \frac{(\omega_{\max} - \omega_{\min}) \text{Rank}_i}{K}, \quad (8)$$

where Rank_i is the position of the i -th particle when they are ordered based on their particle best fitness, K is the number of particles, and ω_{\min} and ω_{\max} are the minimum and maximum values of the inertia weight respectively. In the velocity Eq. (6), the portion $r_1 C_1 \text{rand}_1(\vec{X}_{pbest,i} - \vec{X}_i(t))$ is related to the personal experience of the particles when the portion $r_2 C_2 \text{rand}_2(\vec{X}_{gbest,i} - \vec{X}_i(t))$ is related to the interactive influence among the particles. In fact, the portion $r_2 C_2 \text{rand}_2(\vec{X}_{gbest,i} - \vec{X}_i(t))$ indicates that the particles should neglect their personal experience and adapt their behaviors with the most successful particle in the neighborhood. According to Eq. (7), the updating velocity of the particles consists of three parts: the first part indicates the particles' velocity, the second part shows the personal experience and the third part shows the interactive behavior of the particles [42] and [43]. Referring to Eq. (7) it can be found that the best position of the particles happen with $P_{best,i}$. If any updated velocity goes beyond V_{\max} , it is limited to V_{\max} using Eq. (9):

$$\vec{V}_i(t+1) = \text{sign}(\vec{V}_i(t+1)) \cdot \min(|\vec{V}_i(t+1)|, V_{i,\max}). \quad (9)$$

If the velocity becomes more than this value, V_{\max} is assigned to it. If the velocity becomes fewer than V_{\min} ,

V_{\min} is assigned to it. Thus:

$$v_{\min} \leq \vec{V}_i(t+1) \leq v_{\max}. \quad (10)$$

In this situation, the particle will remain in a specific part of the inertia weight Ω . Here, it is supposed that w will change linearly from 0.4 to 0.9. The flowchart of the proposed algorithm for the adjustment of the parameters is shown in Fig. 4. In order to gain a rapid convergence rate for the proposed method as well as to find the accurate optimal solutions, the values used for the algorithm are shown in Tab. 1. The initial population can be chosen randomly and the proposed algorithm will move toward the optimal solutions according to the pre-determined number of populations until the termination criterion is satisfied. It can be the maximum of generation number, the objective function value and the mean value of the population.

Tab. 1: Parameters used in AIWPSO.

Parameters	Values
Generations number	50
Swarms number	4
Particles number	50
C_1	2
C_2	2
ω_{\min}	0.3
ω_{\max}	0.95

5. Simulation Results and Discussion

The simulations are implemented in the MATLAB software environment. In the stability analysis of the grid, the base frequencies are 50 and 60 Hz which here 60 Hz is selected [44]. Also, this paper uses phasor method and the base frequency in the simulations. The values of the transmission system, generator and SSSC are given in Tab. 2. In order to compare the effectiveness of the proposed approach, the simulations are done in different statuses. Here, the three-phase short circuit error with the ground is investigated. The disturbances are applied at $t = 1$ s. The main purpose is to stabilize the network by the use of the proposed algorithm as well as the AIWPSO algorithm.

5.1. SMIB Power System

The SSSC is a solid state VSC which can generate a controllable AC voltage. This device is in series with the line so that inject a variable voltage V_s to the transmission line. This process can indirectly change the line impedance and the power flow direction. The injected voltage (V_s) phase has $\pi/2$ degree difference with the line current phase; by changing the polarity of V_s , a

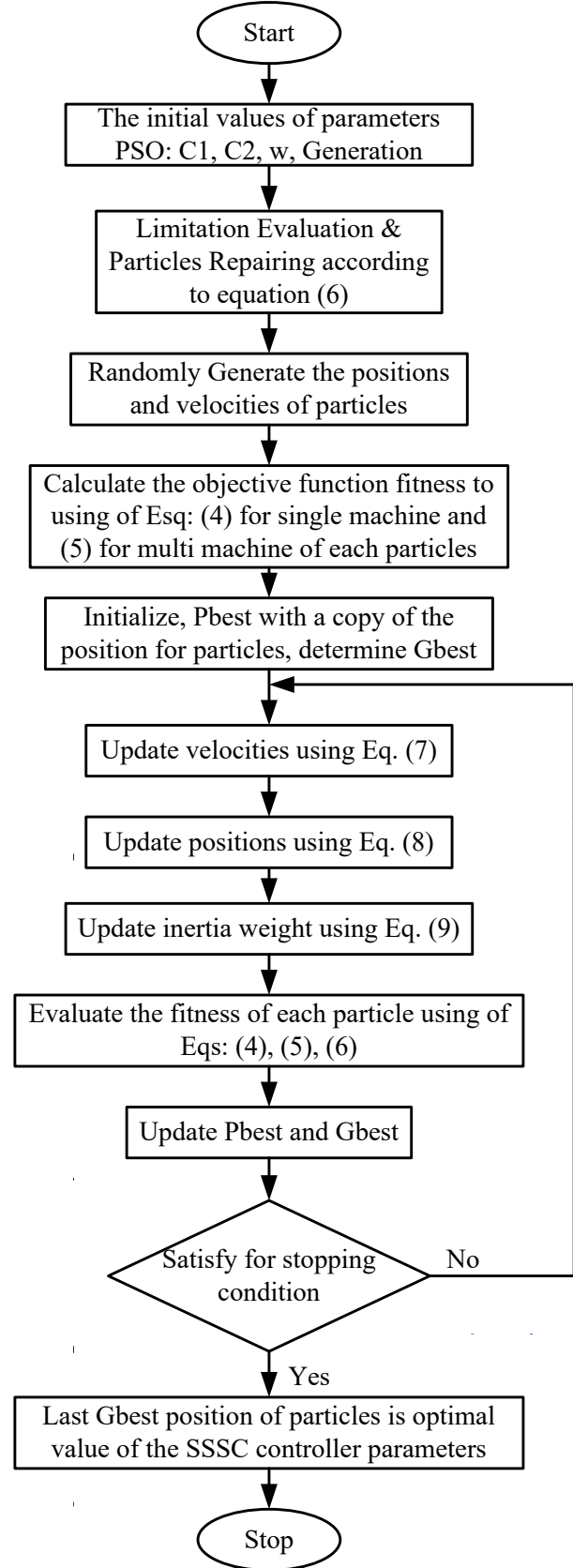


Fig. 4: Schematic representation of AIWPSO optimization approach.

Tab. 2: System parameters and initial conditions.

Power system	Content	Parameters
Single-machine	Generator	$S_n = 1900$ MVA, $V = 15.7$ kV, $X_d = 1.305$, $X_q = 0.474$, $X'_n = 0.296$, $X'_q = 0.18$, $X''_d = 0.252$, $R_s = 0.003$, $f = 60$ Hz, $T_d = 1.01$ s, $T'_d = 0.053$ s, $T'_{q0} = 0.1$ s, $H = 3.7$ s
	Excitation System	$K_a = 200$, $T_n = 0.001$ s, $K_e = 1$, $K_f = 0.001$
	Transformer	900 MVA, 15.7/500 kV, 60 Hz, $R_1 = R_2 = 0.0027$, $L_1 = L_2 = 0.08$, $R_m = L_m = 500$
	Lines	Length of line1=line 2 = 250 Km, $R = 0.02546$ W·Km ⁻¹ , $L = 0.0009337$ H·Km ⁻¹ , $C = 12.74e^{-9}$ F·Km ⁻¹
	SSSC	$S_n = 100$ MVA, $V_n = 500$ KV, $R = 0.00533$, $L = 0.16$, VDC = 40 KV, $K_p = 0.00375$, $K_i = 0.1875$
	Load	Load 1 = 100 MW, Load 2 = 50 MW
Multi-machine	Generators	$S_1 = 1200$ MVA, $S_2 = 1600$ MVA, $V = 15.7$ kV, $f = 60$ Hz, $T_d = 1.01$ s, $T'_n = 0.053$ s, $T'_{q0} = 0.1$ s, $R_s = 0.003$, $X_d = 1.305$, $X'_d = 0.296$, $X'_q = 0.252$, $X_q = 0.474$, $X'_q = 0.18$, $H = 3.7$ s
	Transformer	$S_1 = 1200$ MVA, $S_2 = 1600$ MVA, 15.7/500 kV, $R_1 = R_2 = 0.0027$, $L_1 = L_2 = 0.12$, $R_m = L_m = 500$
	Lines	Length of line1 = line 2 = 250 Km, Length of line 3 = 50 Km, Length of line 4 = 15 Km, $R = 0.02546$ W·Km ⁻¹ , $L = 0.0009337$ H·Km ⁻¹ , $C = 12.74e^{-9}$ F/Km
	Loads	Load 1 = 100 MW, Load 2 = 50 MW, Load 3 = Load 4 = Load 5 = Load 6 = Load 7 = 150 MW, 75 MVAR

capacitive or inductive reactance can be applied to the line [45]. For the optimization of the objective function of Fig. 4, the AIWPSO algorithm is employed.

The objective function in the disturbance status is evaluated for each particle in the population. In order to have a suitable speed and convergence, the acceptable range for each parameter should be determined. In this end first finding population should be evaluated in a wide range of variation and then by the acceptable goal function, the acceptable range of each parameter is determined. The best optimal values for the SSSC controller are found in 100 iterations which as shown in Tab. 3. The optimal values are found by AIWPSO algorithm for three-phase fault. In order to demonstrate the ability and accuracy of the proposed method, the power system with the obtained values for the SSSC controller is examined in different disturbances. To demonstrate the suitable effectiveness of the approach, different cases are shown as following:

- Faulted power system without the controller.
- Power system with controller and adjusted parameters GA.
- Power system with controller and adjusted parameters by AIWPSO.

1) Three-Phase Fault Between Bus 1 and Bus 3 at Point A (Nominal Condition)

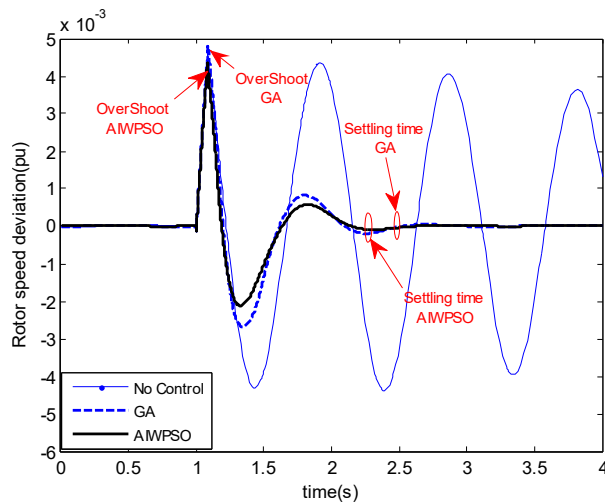
The simulation results for the three-phase fault between the buses 1 and 3 at the point A and middle

of one of the parallel lines in the nominal loading are shown in Fig. 5 over 5 cycles ($Pe = 0.78$). Fig. 5(a) shows the speed deviation in pu. Figure 5(b) shows the rotor angle in degree and Fig. 5(c) shows the injected voltage to the SSSC. Figure 5(d) shows the phase voltage V_t near the generator in pu and Fig. 5(e) shows the power of the system buses. For a transient disturbance in the system, the rotor speed and angle variations increase such that the voltage level in the near buses reduces; it means a voltage collapse has happened. In order to compensate this voltage collapse, the SSSC controller detects the instability of the grid by the use of the rotor angle feedback. According to the instability, severity the required signal is applied to the SSSC exciter shown in Fig. 5(d).

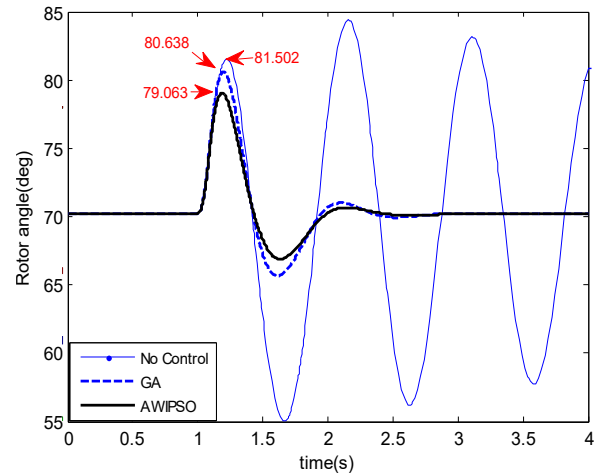
It is seen that the most variations have happened with the controller, the rotor angle has moved from $\delta = 70.16^\circ$ to $\delta = 81.502^\circ$ in the first oscillation. When an AIWPSO controller is used in the first variation, it reaches to $\delta = 79.063^\circ$. Also, by using AIWPSO algorithm, oscillation and time damping have been decreased in comparison to GA.

Tab. 3: Optimal parameter setting controller for SMIB.

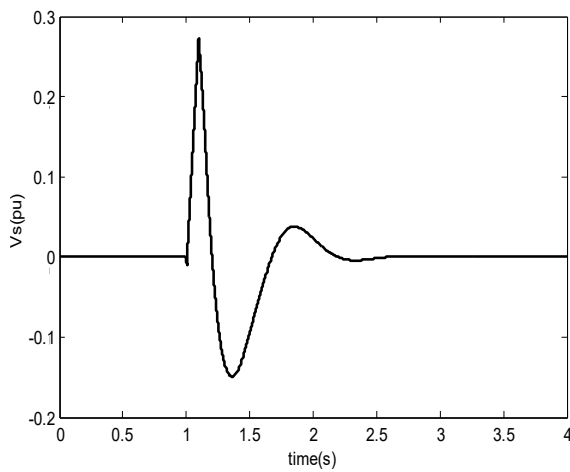
Parameter controller SSSC	AIWPSO	GA	Range
K_p	67.1940	76.3128	20–80
T_{1P}	0.8329	0.9059	0.01–1
T_{2P}	0.2545	0.4396	0.01–1
T_{3P}	0.6456	0.889	0.01–1
T_{4P}	0.8872	0.9107	0.01–1



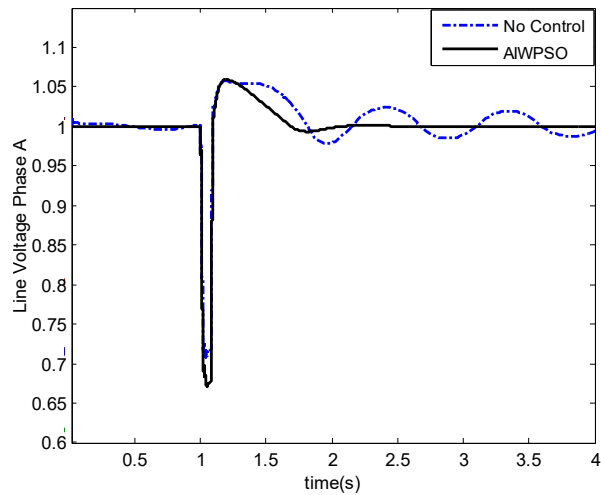
(a) Rotor speed deviation.



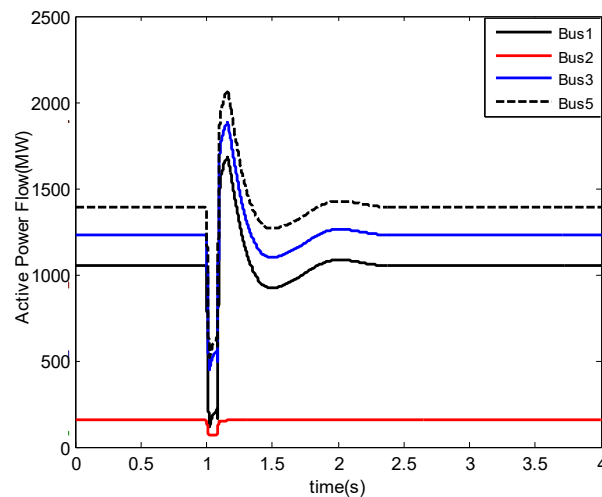
(b) Rotor angle deviation.



(c) SSSC controller output signal at faulty condition.



(d) Comparison of line voltage near generator.



(e) Active power-flow for whole buses nearing disturbance.

Fig. 5: Simulation results for case I (Three-phase fault between bus1 and bus 3 at point A and nominal loading).

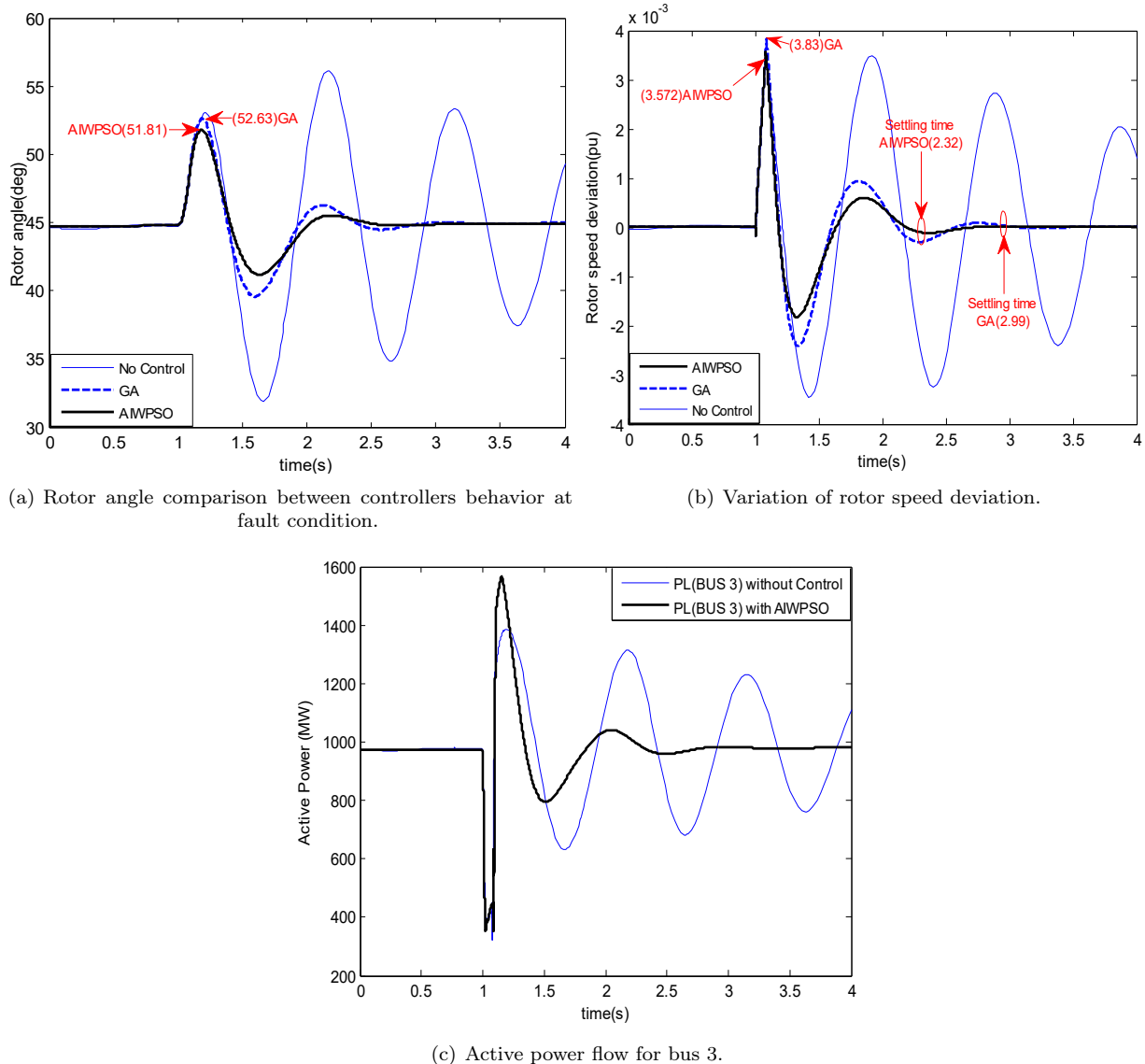


Fig. 6: Simulation results for case II (Three-phase fault at L_1 line and light loading condition).

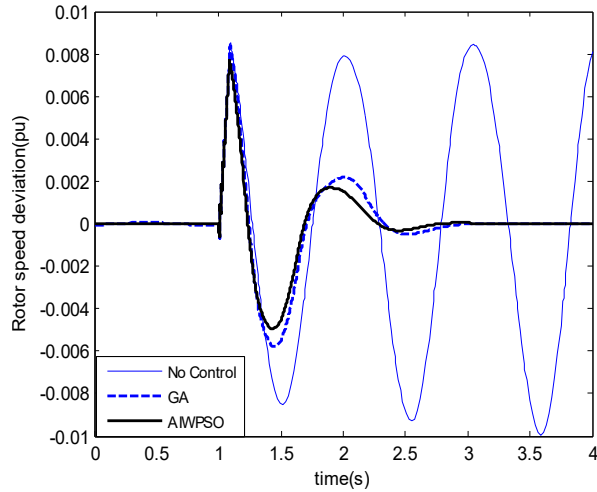
2) Three-Phase Fault at L_1 Line (Light Loading Condition)

In order to demonstrate the capability of the proposed controller, a three-phase fault over 5 cycles at the point A is in L_1 line for light loading is simulated. The generator rotor angle, speed deviation and the active power of the phase are shown in Fig. 6. The generator is at first at the operating point of $\delta = 34.7^\circ$ and $P_e = 0.6$ pu and after the fault, its angle reaches $\delta = 51.81^\circ$ with AIWPSO controller and $\delta = 52.63^\circ$ with GA controller. It can be deduced from these figures that the system oscillation can be damped quickly. The oscillation is improved using approach AIWPSO versus to genetic algorithm. The reason is that the SSSC has changed the reactance of the line by injection of V_s

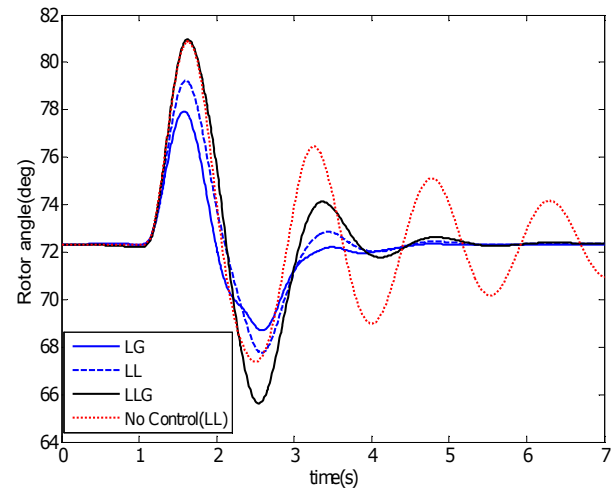
to the system. So the power flow direction has been changed.

3) Three-Phase Fault Between the Buses 3 and 4 at Point B

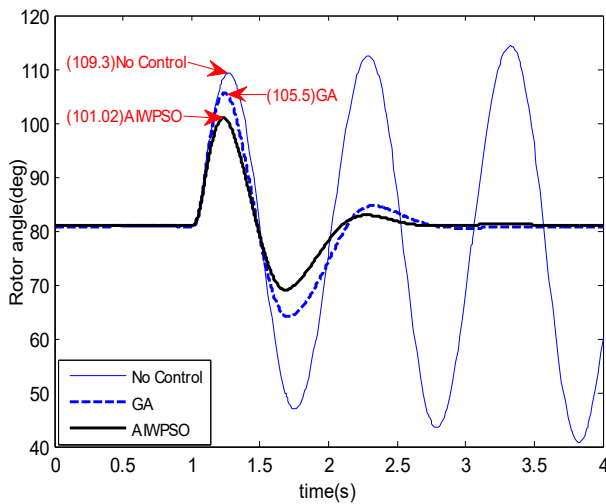
The simulation results using the proposed method is shown in Fig. 7. Here, a three-phase fault to ground at 83 ms for the heavy loading at point B happens. It as seen the rotor angle has started from $\delta = 82^\circ$, $P_e = 1.04$ pu and reached the maximum value of $\delta = 101.02^\circ$ using AIWPSO controller. When the angle variation for this case is more than the other cases, the dynamic stability of the system is largely improved by the proposed controller.



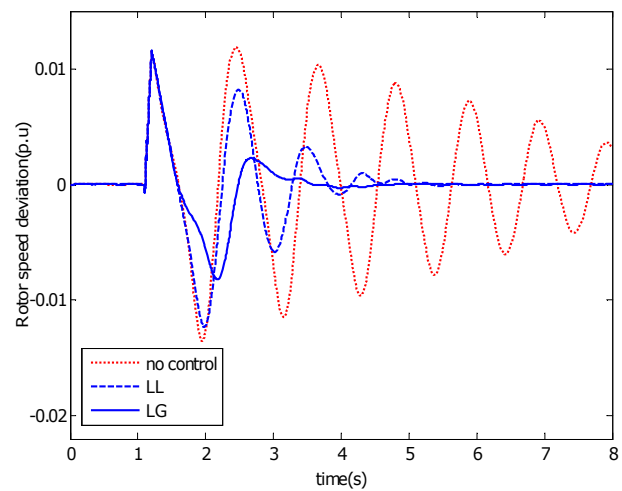
(a) Rotor speed deviation.



(a) Rotor angle.



(b) Variation of rotor angle.



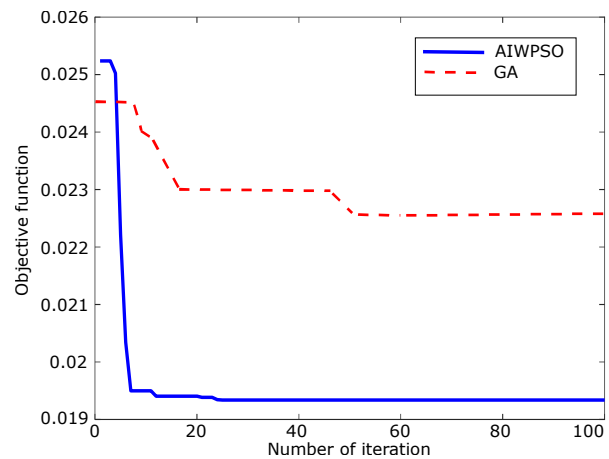
(b) Rotor speed deviation.

Fig. 7: Simulation results for case III (Three-phase fault between the buses 3 and 4 at point B).**Fig. 8:** Power system oscillation under unbalanced faults.

4) Unbalanced Faults Disturbance

Here the behavior of the proposed controller for the unbalanced fault (double line to ground, line to ground and line to line) during 83 ms between buses 1 and 3 is investigated. The system oscillation under unbalanced disturbances is shown in Fig. 8. This case indicates the system response without the controller in the status of line to line fault. The simulation results show that following the L-L fault, the system with no controller becomes unstable and as such the disturbance is controllable. By utilization of the SSSC with the proposed controller, any fault in power system is controllable and by using disturbance control, the system is stable.

In Fig. 9, the objective function with AIWPSO and genetics algorithms respectively converges to 0.0193

**Fig. 9:** Convergence of the objective function for g_{best} .

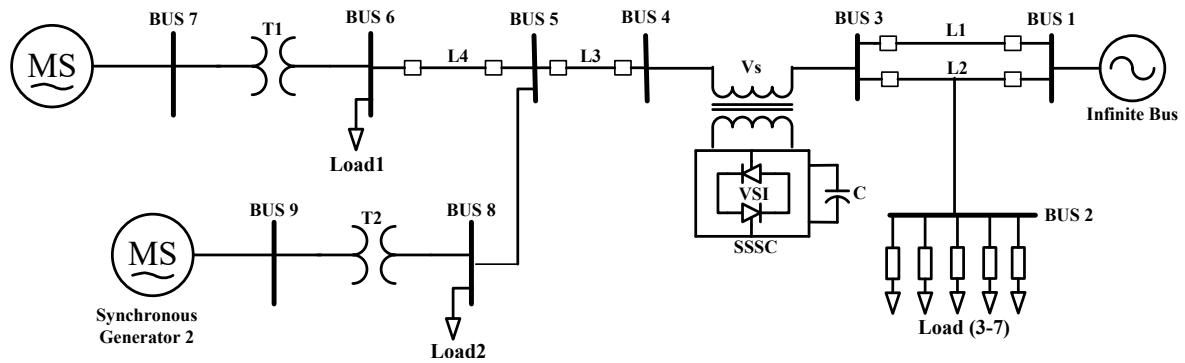


Fig. 10: Schematic of 9 bus multi-machine with SSSC.

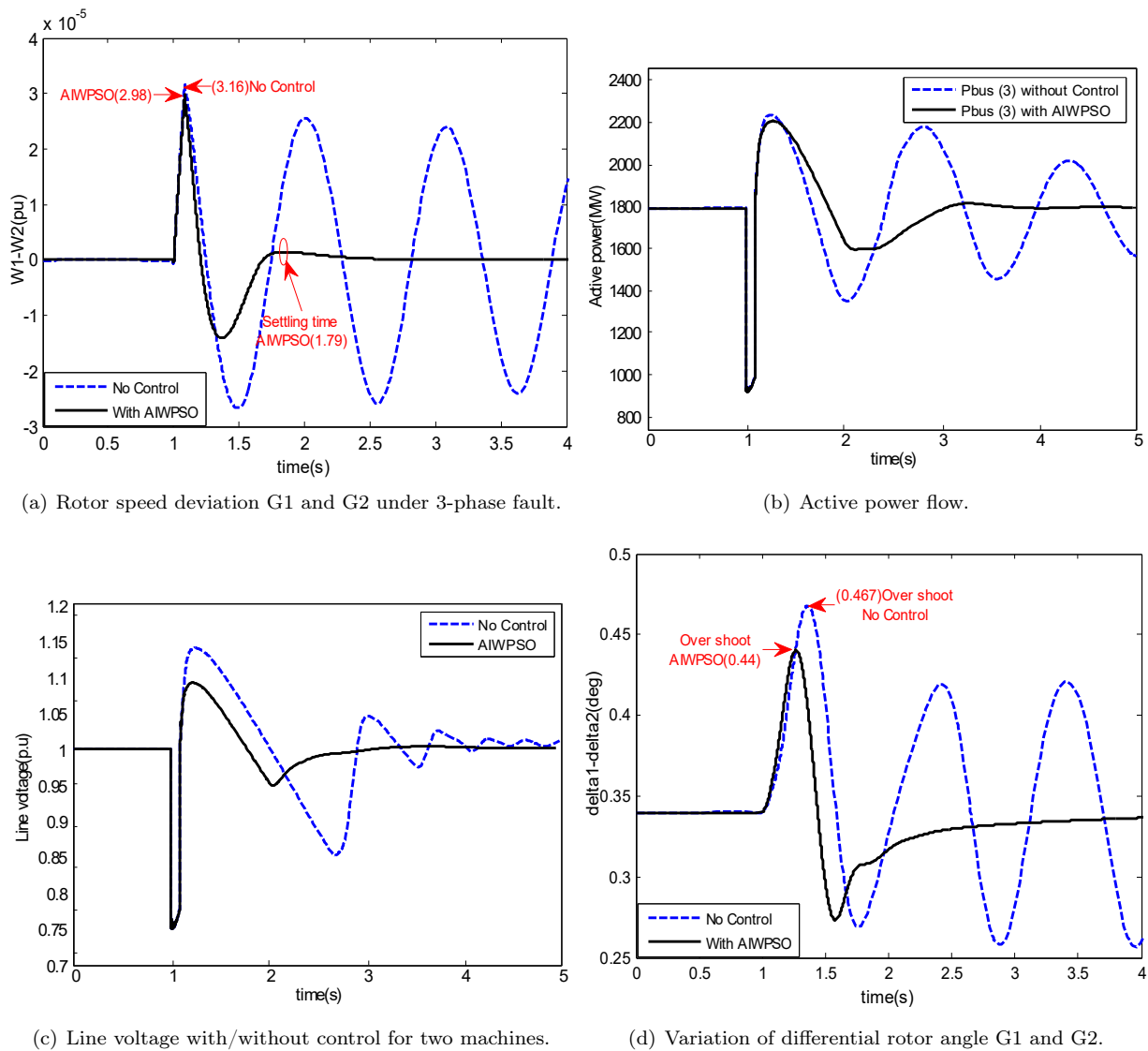


Fig. 11: Results of simulation for multi-machine network.

and 0.0226 for gbest. As a result, AIWPSO algorithm, in comparison to GA in minimizing the objective func-

tion is better and therefore gbest of the AIWPSO algorithm is also better.

5.2. Multi-Machine Power System

In this part, the proposed controller for the SSSC is expanded to the multi-machine case. The case study is a two-machine grid with 9 buses (Fig. 10). The system consists of 2 generators with power 1200 MVA and 1600 MVA, a large 750 MW and 75 MVAR load at bus 2 and some small loads. After the fault in the system, both generators oscillate and the SSSC is used to improve the network stability. The SSSC parameters for the 2-machine system are shown in Tab. 4. Three-phase fault occurs on one of the parallel lines between the buses 1 and 3 occurring over 5 cycles. The simulation results are shown in Fig. 10. They indicate that the system is capable to damp the oscillations in short time after the fault. The diagram shows the power system with and without AIWPSO controller of the SSSC.

Tab. 4: Optimal parameter setting of the propositional controller for multi-machine.

Parameter controller SSSC	AIWPSO	GA	Range
K _P	66.8	76.0128	20–80
T _{1P}	0.9021	0.9238	0.01–1
T _{2P}	0.4236	0.7665	0.01–1
T _{3P}	0.1470	0.4071	0.01–1
T _{4P}	0.9325	0.9637	0.01–1

6. Conclusion

In this paper, the grid transient stability promotion through the SSSC controller was discussed and investigated for power systems. The new AIWPSO algorithm was used to find the optimal amounts of the SSSC controller. The investigated problem, as well as the objective function, was formulated precisely. The satisfying performance of the proposed method was obtained in different cases and the achievements were compared to each other. It was seen that the rotor angle in the first oscillation is large and its maximum value happens in case 3. The oscillation improved when approach AIWPSO is applied. Also, the proposed method was applied to both single-machine and multi-machine systems and it was found that the suggested controller can sufficiently damp the oscillations of both systems.

References

- [1] SHAHGHOLIAN, G. Modelling and simulation of low-head hydro turbine for small signal stability analysis in power system. *Journal of Renewable Energy and Environment*. 2016, vol. 3, iss. 3, pp. 11–20. ISSN 2423-5547.
- [2] ELLITHY, K., S. SAID and O. KAHLOUT. Design of power system stabilizers based on controller for power system stability enhancement. *International Journal of Electrical Power and Energy Systems*. 2014, vol. 63, iss. 1, pp. 933–939. ISSN 0142-0615.
- [3] JAFARI, E., A. MARJANIAN, S. SILAYMANI and G. SHAHGHOLIAN. Designing an emotional intelligent controller for IPFC to improve the transient stability based on energy function. *Journal of Electrical Engineering and Technology*. 2013, vol. 8, iss. 3, pp. 478–489. ISSN 1975-0102.
- [4] MAHMUD, M. A., H. R. POTA, M. ALDEEN and M. J. HOSSAIN. Partial feedback linearizing excitation controller for multimachine power systems to improve transient stability. *IEEE Transactions on Power Systems*. 2014, vol. 29, iss. 2, pp. 561–571. ISSN 0885-0679. DOI: 10.1109/TPWRS.2013.2283867.
- [5] AZIMI, Z. and G. SHAHGHOLIAN. Power system transient stability enhancement with TCSC controller using genetic algorithm optimization. *International Journal of Natural and Engineering Sciences*. 2016, vol. 10, iss. 3, pp. 9–15. ISSN 0885-8977.
- [6] TANG, L. and W. SUN. An automated transient stability constrained optimal power flow based on trajectory sensitivity analysis. *IEEE Transactions on Power Systems*. 2017, vol. 32, iss. 1, pp. 590–599. ISSN 0885-8950. DOI: 10.1109/TPWRS.2016.2551278.
- [7] SHAHGHOLIAN, G. Review of power system stabilizer: Application, modeling, analysis and control strategy. *International Journal on Technical and Physical Problems of Engineering*. 2013, vol. 5, iss. 16, pp. 41–52. ISSN 2077-3528.
- [8] BEHROUZIAN, E., M. BONGIORNO and R. TEO-DORESCU. Impact of switching harmonics on capacitor cells balancing in phase-shifted PWM-based cascaded H-bridge STATCOM. *IEEE Transactions on Power Electronics*. 2017, vol. 32, iss. 1, pp. 815–824. ISSN 0885-8993. DOI: 10.1109/TPEL.2016.2535481.
- [9] BANAEI, M. R. and Z. MOKHTANEZHAD. Voltage stability improvement by location of STATCOM in power system. *Journal of Circuits, Systems and Computers*. 2014, vol. 23, no. 2, pp. 1–13. ISSN 0218-1266. DOI: 10.1142/S021812661450025X.
- [10] FETOUEH, T. and M. S. ZAKY. New approach to design SVC-based stabiliser using genetic algorithm and rough set theory. *IET Generation, Transmission and Distribution*. 2017,

- vol. 11, iss. 2, pp. 372–382. ISSN 1751-8687. DOI: 10.1049/iet-gtd.2016.0701.
- [11] ABD ELAZIM, S. M. and E. S. ALI. Optimal SSSC design for damping power systems oscillations via gravitational search algorithm. *International Journal of Electrical Power and Energy Systems*. 2016, vol. 82, iss. 1, pp. 161–168. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2016.02.023.
 - [12] BAKHSI, M., M. H. HOLAKOOIE and A. RABIEE. Fuzzy based damping controller for TCSC using local measurements to enhance transient stability of power systems. *International Journal of Electrical Power and Energy Systems*. 2017, vol. 83, iss. 1, pp. 12–21. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2016.06.014.
 - [13] MANORANJITHAM, E. and S. ALAGARSAMY. Application of firefly algorithm on optimal power flow control incorporating simplified impedance UPFC model. *International Journal of Electrical Power and Energy Systems*. 2015, vol. 71, iss. 1, pp. 358–363. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2015.03.009.
 - [14] SHAHGHOLIAN, G., A. MOVAHEDI and J. FAIZ. Coordinated design of TCSC and PSS controllers using VURPSO and genetic algorithms for multi-machine power system stability. *International Journal of Control, Automation, and Systems*. 2015, vol. 13, iss. 2, pp. 398–409. DOI: 10.1007/s12555-013-0387-z.
 - [15] HUANG, C. M. and Y. C. HUANG. Hybrid optimisation method for optimal power flow using flexible AC transmission system devices. *IET Generation, Transmission and Distribution*. 2014, vol. 8, iss. 12, pp. 2036–2045. ISSN 1751-8687. DOI: 10.1049/iet-gtd.2014.0096.
 - [16] MILANOVIC, J. V. and Y. ZHANG. Modeling of FACTS devices for voltage sag mitigation studies in large power systems. *IEEE Transactions on Power Delivery*. 2010, vol. 25, iss. 4, pp. 3044–3052. DOI: 10.1109/TPWRD.2010.2052395.
 - [17] SHIVAM, S., I. HUSSAIN and B. SINGH. Real-time implementation of SPV system with DSTATCOM capabilities in three-phase four-wire distribution system. *IET Generation, Transmission and Distribution*. 2017, vol. 11, iss. 2, pp. 495–503. ISSN 1751-8687. DOI: 10.1049/iet-gtd.2016.1032.
 - [18] SHAHGHOLIAN, G. and A. MOVAHEDI. Coordinated design of thyristor controlled series capacitor and power system stabilizer controllers using velocity update relaxation particle swarm optimization for two-machine power system stability. *Revue Roumaine Des Sciences Techniques*. 2014, vol. 59, iss. 3, pp. 291–301. ISSN 0035-4066.
 - [19] SANGEETHA, J. and P. RENUGA. Recurrent ANFIS-coordinated controller design for multi machine power system with FACTS devices. *Journal of Circuits, Systems and Computers*. 2017, vol. 26, iss. 2, pp. 1–14. ISSN 0218-1266. DOI: 10.1142/S0218126617500347.
 - [20] WANG, Y., A. A. HASHMANI and T. T. LIE. Nonlinear coordinated excitation and TCPS controller for multimachine power system transient stability enhancement. *IET Generation, Transmission and Distribution*. 2001, vol. 148, iss. 1, pp. 133–141. ISSN 1751-8695.
 - [21] AL-JOWDER, F. Improvement of synchronizing power and damping power by means of SSSC and STATCOM: A comparative study. *Electrical Power System Research*. 2007, vol. 77, iss. 8, pp. 1112–1117. ISSN 0378-7796. DOI: 10.1016/j.epsr.2006.09.007.
 - [22] SHAHGHOLIAN, G. and A. MOVAHEDI. Power system stabiliser and flexible alternating current transmission systems controller coordinated design using adaptive velocity update relaxation particle swarm optimisation algorithm in multi-machine power system. *IET Generation, Transmission and Distribution*. 2016, vol. 10, iss. 8, pp. 1860–1868. ISSN 1751-8687. DOI: 10.1049/iet-gtd.2015.1002.
 - [23] THIRUMALAIVASAN, R., M. JANAKI and N. PRABHU. Damping of SSR using subsynchronous current suppressor with SSSC. *IEEE Transactions on Power Systems*. 2013, vol. 28, no. 1, pp. 64–74. ISSN 0885-8950. DOI: 10.1109/TPWRS.2012.2193905.
 - [24] PANDA, S. Multi-objective evolutionary algorithm for SSSC based controller design. *Electric Power System Research*. 2009, vol. 79, iss. 6, pp. 937–944. ISSN 0378-7796. DOI: 10.1016/j.epsr.2008.12.004.
 - [25] CASTRO, M. S., H. M. AYRES, V. F. DA COSTA and L. C. P. DA SILVA. Impacts of the SSSC control modes on small-signal and transient stability of a power system. *Electric Power Systems Research*. 2007, vol. 77, iss. 1, pp. 1–9. ISSN 0378-7796. DOI: 10.1016/j.epsr.2006.01.003.
 - [26] JYOTHSNA, T. R. and K. VAISAKH. Design and performance evaluation of SSSC supplementary modulation controller in power systems using SPEF method. *International Journal of Electrical Power and Energy Systems*. 2012, vol. 35, iss. 1, pp. 158–170. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2011.10.008.

- [27] KHADANGA, R. K. and J. K. SATAPATHY. Time delay approach for PSS and SSSC based coordinated controller design using hybrid PSO-GSA algorithm. *International Journal of Electrical Power and Energy Systems*. 2015, vol. 71, iss. 1, pp. 262–273. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2015.03.014.
- [28] JOWDER, F. A. L. Influence of mode of operation of the SSSC on the small disturbance and transient stability of a radial power system. *IEEE Transactions on Power Systems*. 2005, vol. 20, iss. 1, pp. 935–942. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2015.03.014.
- [29] PANDA, S. and N. P. PADHY. Comparison of particle swarm optimization and genetic algorithm for FACTS-based controller design. *Applied Soft Computing*. 2008, vol. 8, iss. 4, pp. 1418–1427. ISSN 1568-4946. DOI: 10.1016/j.asoc.2007.10.009.
- [30] RAVI, K. and M. RAJARAM. Optimal location of FACTS devices using improved particle swarm optimization. *International Journal of Electrical Power and Energy Systems*. 2013, vol. 49, iss. 1, pp. 333–338. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2012.12.008.
- [31] MONDAL, D., A. CHAKRABARTI and A. SENGUPTA. Optimal placement and parameter setting of SVC and TCSC using PSO to mitigate small signal stability problem. *Electrical Power and Energy Systems*. 2012, vol. 42, iss. 1, pp. 334–340. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2012.04.017.
- [32] FALEHI, A. D., M. ROSTAMI, A. DOROUDI and A. ASHRAFIAN. Optimization and coordination of SVC-based supplementary controllers and PSSs to improve power system stability using a genetic algorithm. *Turkish Journal of Electrical Engineering and Computer Sciences*. 2012, vol. 20, iss. 5, pp. 639–654. ISSN 1300-0632. DOI: 10.3906/elk-1010-838.
- [33] NICKABADI, A., M. M. EBADZADEH and R. SAFABAKHSH. A novel particle swarm optimization algorithm with adaptive inertia weight. *Applied Soft Computing*. 2011, vol. 11, no. 4, pp. 3658–3670. ISSN 1568-4946. DOI: 10.1016/j.asoc.2011.01.037.
- [34] MAHDAVIAN, M., A. MOVAHEDI, G. SHAHGHO-LIAN and M. JANGHORBANI. Coordinated control of PSS and variable impedance devices by using AVURPSO to enhance the stability in power system. In: *Proceeding of the IEEE/ECTICON*. Phuket: IEEE, 2017, pp. 407–410. ISBN 978-1-5386-0449-6. DOI: 10.1109/ECTICON.2017.8096260.
- [35] PANDA, S. Differential evolution algorithm for SSSC-based damping controller design considering time delay. *Journal of the Franklin Institute*. 2011, vol. 348, iss. 8, pp. 1903–1926. ISSN 0016-0032. DOI: 10.1016/j.jfranklin.2011.05.011.
- [36] KHEDERZADEH, M. and A. GHORBANI. Impact of VSC-based multilane FACTS controllers on distance protection of transmission lines. *IEEE Transactions on Power Delivery*. 2012, vol. 27, iss. 1, pp. 32–39. ISSN 0885-8977. DOI: 10.1109/TPWRD.2011.2168428.
- [37] GONZALEZ, J. M., C. A. CANIZARES and J. M. RAMIREZ. Stability modeling and comparative study of series vectorial compensators. *IEEE Transactions on Power Delivery*. 2010, vol. 25, iss. 2, pp. 1093–1103. ISSN 0885-8977. DOI: 10.1109/TPWRD.2009.2034905.
- [38] PETER, W. S. and M. A. PAI. *Power system dynamics and stability*. 1st ed. New Jersey: Stipes Publishing, 1998. ISBN 978-1588746733.
- [39] PANDA, S., S. C. SWAIN, P. K. RAUTRAY, R. K. MALIK and G. PANDA. Design and analysis of SSSC-based supplementary damping controller. *Simulation Modelling Practice and Theory*. 2010, vol. 18, iss. 9, pp. 1199–1213. ISSN 1569-190X. DOI: 10.1016/j.simpat.2010.04.007.
- [40] KUNDUR, P. *Power system stability and control*. 1st ed. New York: McGraw-Hill Education, 1994. ISBN 978-0070359581.
- [41] DEL VALLE, Y., G. K. VENAYAGAMOORTHY, S. MOHAGHEGHI, J. C. HERNANDEZ and R. G. HARLEY. Particle swarm optimization: basic concepts, variants and applications in power systems. *IEEE Transactions on Evolutionary Computation*. 2008, vol. 12, iss. 2, pp. 171–195. ISSN 1089-778X. DOI: 10.1109/TEVC.2007.896686.
- [42] ZHAO, B., C. X. GUO and Y. J. CAO. A multiagent-based particle swarm optimization approach for optimal reactive power dispatch. *IEEE Transactions on Power Systems*. 2005, vol. 20, iss. 2, pp. 1070–1078. ISSN 0885-8950. DOI: 10.1109/TPWRS.2005.846064.
- [43] PANIGRAHI, K., V. R. PANDI and S. DAS. Adaptive particle swarm optimization approach for static and dynamic economic load dispatch. *Energy Conversion and Management*. 2008, vol. 49, iss. 6, pp. 1407–1415. ISSN 0196-8904. DOI: 10.1016/j.enconman.2007.12.023.
- [44] FARAHANI, M. Damping of subsynchronous oscillations in power system using static synchronous series compensator. *IET Generation*,

Transmission and Distribution. 2012, vol. 6, iss. 6, pp. 539–544. ISSN 1751-8687. DOI: 10.1049/iet-gtd.2011.0625.

- [45] SHAHGHOLIAN, G. and J. FAIZ. Static synchro-nous compensator for improving performance of power system: A review. *International Review of Electrical Engineering*. 2010, vol. 5, no. 5, pp. 2333–2342. ISSN 1827-6660.

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